European accelerator-based neutrino projects

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Future neutrino projects in Europe will follow two distinct time lines. On the medium term, they will be dominated by the CERN-Gran Sasso long-baseline project, with two experiments OPERA and ICARUS, mainly concentrated on τ appearance. On the longer term, several projects are under discussion. A new proton driver at CERN that accelerates a 4 MW beam to 2.2 GeV of energy would open the possibility of a low-energy super-beam, possibly sent to the French laboratory under the Frejus. A new radioactive heavy ion facility could produce a pure ν_e beam, to be used independently or simultaneously with the super-beam. In the framework of R&D for Super-Beam and Neutrino Factory, the HARP experiment is studying hadron production at low energies on various targets.

1 Introduction

Traditionally, accelerator-based neutrino physics in Europe has been centred around CERN. Also for the future, this laboratory is expected to play a leading role in neutrino physics, despite the heavy commitment in the construction of LHC.

Due to the small atmospheric neutrino mass difference squared, the attention of the neutrino community is presently shifted towards long-baseline project. The CERN neutrino beam to Gran Sasso is higher in energy with respect to the Japanese [1] or American [2] projects, and will have the unique feature of being well above threshold for τ lepton production, in order to confirm the $\nu_\mu \to \nu_\tau$ nature of the atmospheric oscillations.

The OPERA detector is a dedicated experiment to search for τ appearance using topological informations, while ICARUS is a more versatile apparatus, that could reach similar τ identification capabilities, provided a sufficient number of modules is built.

On the longer term, the European projects are focused towards the possibility of building a super-beam based on a Superconducting Proton Linac (SPL), that also would be the first building block of a CERN-based neutrino factory. To estimate the flux of neutrinos produced in a super-beam, or the number of muons accelerated in a neutrino factory, a dedicated experiment (HARP) is presently under way. The Harp detector, built in a very short time, has taken data in summer 2001 and will have a second run in summer 2002 at the CERN PS. The goal is to measure total and differential cross sections for proton interactions with a large variety of targets, with energy in the range

3-15 GeV.

2 The Neutrino beam from CERN to Gran Sasso

As stated in the introduction, the CERN beam to Gran Sasso has the unique characteristic of being at a sufficiently high energy to produce a detectable number of τ leptons in charged current ν_τ interactions. This is a natural consequence of using a high-energy proton driver (400 GeV from the CERN SPS), having as a natural target the Gran Sasso lab near Rome (distant 732 km from CERN) and of the practical difficulties of building a near station, that makes hard to conceive disappearance measurements.

Civil engineering construction started on Oct 12, 2000; they will consist of 3 km of new tunnels and caverns: 700 m for the proton line to the target, 1 km of decay tube, plus various connections. Overall it will mean 45000 m^3 of rock removal, and 12000 m^3 of concrete added to reinforce the walls. The main properties of the CNGS beam are listed in table 2.

Baseline	732 km
Maximum depth	11.4 km
POT/extraction	2.4×10^{13}
POT/year	4.5×10^{19}
Flux at Gran Sasso	$3.5\times10^{12}/y/100m^2$
ν interactions	2500/kt/y
$< E_\nu >$	17 GeV
$\%\nu_\mu$	2.0
$\%(\nu_e + \bar{\nu}_e)$	0.8

Table 1: Main properties of the CNGS beam

The beam target will be 2 meters long, made of 10 cm long graphite (pure carbon) rods, interspaced to minimise absorption of pions with small transverse momentum with respect to the beam direction. Due to the strong thermical shocks, the whole system is cooled with helium. Secondaries produced in interactions with the target are focalised by a horn/reflector system. The horn will be 6.5 m long, with a diameter of 70 cm, and able to sustain a current of 150 kA for 1 ms, with a tolerance rate of 95% survival probability after 5×10^7 pulses. A horn prototype has already been built and tested, and survived 1.5 million pulses.

The beam transverse profile will be checked using two muon detectors at the end of the decay tunnel; the beam width at the far location is more than one kilometre, and approximately flat for a radius of about 500 m, much larger

than the expected width of the detectors. Systematic uncertainties on the beam can arise from misalignment of the various components. As a reference, a 3% variation in the number of ν_μ in Gran Sasso could result from:

- the horn being off-axis by 6 mm
- the reflector being off-axis by 30 mm
- the beam being off-axis by 1 mm on the target
- an overall misalignment of 0.5 mrad

Beam alignment can be further checked in the Gran Sasso site, looking for the muons produced by neutrino interactions in the upstream rock. However, we have to bear in mind that flux systematics is not that relevant when doing an appearance experiment with few candidate events.

Possible upgrade schemes for the PS/SPS complex, in order to increase the neutrino flux, have been extensively studied [3]. It was found out that most of the components are at their limits. A gain of a factor 1.5 seems feasible; however, a factor 3 seems the absolute maximum, even if large investments are made.

The Gran Sasso laboratory from INFN (Laboratori Nazionali del Gran Sasso, LNGS) is operational since 1987, and offers an easy access from a motorway tunnel, and 1500 meters of rock overburden. The completion of the first generation of experiments (e.g. MACRO) leaves space in two large underground hall (B and C), oriented towards CERN, to perform long-baseline neutrino experiments. The two experiments foreseen for the long-baseline project are OPERA [4], already fully approved as CNGS1, a dedicated experiment to look for τ kink in a hybrid emulsion system, and ICARUS [5], of which the first module has already been built and successfully tested, a general-purpose detector based on a liquid Argon TPC.

3 OPERA

The requirement to have a large mass and a space resolution of the order of 1 μ m has lead to the choice of hybrid emulsions as basic detector component. A basic cell is composed of 1 mm lead planes, separated by an emulsion layer made of two 50 mm emulsion sheets separated by 100 μm plastic base. 56 such lead-emulsion cells constitute a brick, 3000 bricks, together with an extruded scintillator plane for quasi-online identification of interesting interactions are a module, 24 modules, completed with a muon spectrometer, form a supermodule. The experiment will be made of 3 such supermodules, for a total mass of

about 2 ktons. The emulsion surface will be 176000 m^2; as a comparison, that of CHORUS was about 500 m^2. Given the very large amount of emulsion surface, finding few τ events, for an average τ decay length of half a millimetre, is an extremely challenging task. The first step will be the use of the scintillator tracker plane behind the bricks to identify where neutrino interactions take place. These bricks are removed from the wall, with a rate of about 40 bricks per day. They are exposed for a short period to cosmic rays in a shallower location, always in Gran Sasso, to provide a reference for the alignment, and then the emulsions are developed. Then, a search for a neutrino vertex and a decay candidate is performed quasi-online by various scanning stations. The goal is to understand if the brick extracted is sufficient for τ search, or additional nearby bricks have to be extracted. Finally, about 500 squared meters of emulsions (a factor 100 more than at CHORUS) are sent to the scanning labs.

The scanning speed is a fundamental factor to ensure the success of the experiment. A factor 20 improvement with respect to the present speed is expected from the use of the S-UTS technology presently under development in the Japanese laboratory of Nagoya University. This system is based on a fast CCD camera (3000 frames per second) connected to microscopes, with continuous movement on the x-y plane. The z position is determined by the focusing plane of the microscopes, controlled by pizo-attenuators. The scanning speed envisaged is 20 sqcm per hour, and the amount of data reduction from pixel to track of the order of 10^5.

The strategy for τ search is based first on finding a vertex, i.e. a common starting point for tracks with $\tan\theta < 0.4$, that are followed back until not any more found in two successive layers. Including geometrical losses, a vertex finding efficiency of 80% is expected. Then the search is split in two, depending on weather the τ decays in the same lead layer (short decays) or in the next. In the first case, the requirement is to have the momentum of the primary track above 1 GeV, and an impact parameter larger than a value, dependent on the z position, between 5 and 20 μm. In case of long decays, the requirement is to have a kink angle of 20 mrad with respect to the initial track (the kink angle resolution is about 3 mrad). The signal efficiency for several event categories is shown in table 3, and the number of expected backgrounds in table 3.

In absence of signal, OPERA can exclude at 90% C.L. $\nu_\mu \rightarrow \nu_\tau$ oscillations for $\Delta m^2 < 1.2 \times 10^{-3} eV^2$ at full mixing, and $\sin^2 2\theta < 5.7 \times 10^{-3}$ at large Δm^2. The number of expected events for signal and background for various values of Δm^2 and maximal mixing are shown in table 3

	DIS long	QE long	DIS short	Overall
$\tau \to e$	2.7	2.3	1.3	3.4
$\tau \to \mu$	2.4	2.5	0.7	2.8
$\tau \to h$	2.8	3.5	-	2.9
Total	8.0	8.3	1.3	9.1

Table 2: τ identification efficiency for OPERA in various decay channels, for Deep Inelastic Scattering (DIS) and Quasi-Elastic (QE) events, in the long and short configuration

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	Total
Long decays	0.15	0.29	0.24	0.67
Short decays	0.03	0.04	-	0.07

Table 3: Background for τ identification in number of events for long and short decays.

4 ICARUS

The ICARUS detector is composed of a large liquid Argon TPC, that combines big mass and a granularity of the order of 1 mm, being a veritable electronic bubble chamber. Its resolution and particle identification capabilities allow this kind of detector to contribute to a vast and versatile physics program, that includes study of atmospheric neutrinos, solar neutrinos, nucleon decay and of course neutrinos from the long baseline beam.

Drifting electrons for distances of the order of 1 meter, needed to achieve a sufficient detector mass, requires an extreme purity of the liquid Argon: the tolerance is a concentration of electronegative impurities at the level of 0.1 parts per billion, that was finally achieved after 10 years of R&D.

A 600 ton module has been built during the last years in Pavia, and successfully tested this summer with cosmic ray data. Many long (20 meters) muon events were observed, as well as other interesting events such as electromagnetic showers, stopping muons and strange particles.

This 600 ton detector will be transported to Gran Sasso at the beginning of 2003. The ICARUS technology is very well-suited for τ search, using a kine-

Δm^2	1.2×10^{-3}	2.4×10^{-3}	5.4×10^{-3}	BG
	2.7	10.8	53.5	0.75

Table 4: Number of expected signal events (with efficiency included) and of background, after 5 years of CNGS operation for the OPERA detector

matic approach, complementary to the topological one of OPERA. However, 600 tons are not sufficient to produce enough events when the tight cuts necessary for large background suppression are applied. The ICARUS collaboration has recently proposed [6] an upgrade to 5 modules, for a total fiducial mass of 2.35 kton. Golden $\tau \to e$ events can be identified cutting on fiducial volume, electron momentum, visible energy, electron P_t and Q_t and missing momentum. The best sensitivity is obtained combining several variables in a common likelihood, and efficiencies and backgrounds for a 3 kton ICARUS (table 4) is similar to that of OPERA. Due to its good electron identification, ICARUS

τ decay mode	1.6	2.5	3.0	4.0	BG
$\tau \to e$	3.7	9	13	23	0.7
$\tau \to \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \to \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	4.9	11.9	17.2	30.5	0.7

Table 5: Signal events for different values of Δm^2 (in units of $10^{-3} eV^2$) and expected number of background events after 5 years of data taking for a 3 kton ICARUS detector.

will also be able to perform a search for $\nu_\mu \to \nu_e$ oscillations, improving by some factors the present limit on $\sin^2 2\theta_{13}$.

5 The CERN-Frejus Super-Beam

In the next 15-20 years the main commitment of CERN will be the construction and operation of LHC and its detectors. However, the European neutrino community is very active in trying to shape a next-generation neutrino program, in the context of a future CERN-based neutrino factory. The first brick of such a machine would be a low energy (2.2 GeV) high power (4 MW) proton linac[7].

Independently of the neutrino factory, this machine would be a considerable improvement to the CERN accelerator complex, since it will increase PS beam intensity, triple the brilliance of the LHC beam, supply the present ISOLDE facility with 5 times more current (or up to 100 times for Super-ISOLDE), and allow the construction of a low-energy superbeam.

Focusing the pions in the energy range of their maximal production, the resulting mean neutrino energy is about 250 MeV, an ideal energy for a water Cerenkhov detector. At this energy, the maximum of the oscillation occurs for a baseline of about 130 Km, the distance between CERN and the Frejus tunnel. Due to the civil engineering work foreseen to build a second motorway gallery, it is conceivable to propose building there a large Cerenkhov detector, to be

used for proton decay, supernova and beam neutrinos, like that proposed by the UNO collaboration [8]. Considering 400 kton of fiducial mass, a π^0/e separation with 0.1 % confusion and efficiency around 70%, the 90% C.L. sensitivity to $\sin^2 2\theta_{13}$ would be in the range of 5×10^{-4} after 5 years for the current values of Δm^2. A ten times smaller exposure would already allow measuring $\sin^2 \theta_{23}$ at 1% level and Δm^2_{23} with a precision of 10^{-4}. For CP violation studies, even in the case of a favourable choice of parameters, 400 kton are needed, for 2 years of running with neutrinos and 10 years with antineutrinos.

6 The beta-beam

A recent interesting possibility [9] is producing a neutrino beam from the decay of radioactive ions collected in a storage ring. Antineutrinos would be for instance produced by the decay ${}^6He^{++} \rightarrow^6 Li^{+++}\bar{\nu}_e e^-$, and neutrinos from similar decays of ${}^{18}Ne$. The advantage of this approach with respect to the "traditional" Neutrino factory is that despite the lower intensities of the stored beam, the much larger quality factor Γ/E_0 for ions produces a very collimated neutrino beam, leading to fluxes in the far detector similar to those of a super-beam, for comparable energies. The produced beam will be extremely clean and well-known, and of only the electron neutrino flavour. Moreover, it is possible to think of an experiment combining the beta-beam and the super-beam, that would produce an almost pure ν_μ beam, separated from the ν_e beta-beam using timing information. Such a system would have the two-beam feature of the neutrino factory, but it will not need a magnetic detector to distinguish oscillated and beam events. Therefore, larger detector with lower threshold can be used (like a water Cerenkov), putting them at shorter distance to minimise matter effect. A high-intensity combination of super-beam and beta-beam could search for T-violation in an extremely convincing way.

7 Other experiments

The HARP detector, presently running at CERN, is not strictly speaking a neutrino experiment, but it will provide measurement of hadron production at small and large angles for a variety of target material of interest for neutrino beams. In particular large angle pion production is important in the design of the focusing system of a Neutrino Factory and a Super-Beam. It will also use cryogenic targets made of liquefied gases for hadronic production in the atmosphere in the region of interest of atmospheric neutrinos, as well as the measurement of replicas of existing neutrino targets (K2K, MiniBOONE). Several million of events have been collected in summer 2001, and a similar

statistics will be collected this year. Since several sources of data-taking inefficiency have been removed, the number of useful events is expected to increase by a factor of approximately 5.

The possibility of using the existing AD ring as a muon accumulator for a "baby" neutrino factory to measure low-energy neutrino cross section was studied [10]. The interesting result was that these muons are already accumulated in the present antiproton running mode, and thus a neutrino beam is already existing there. Unfortunately, quantitative estimate showed that obtaining a sufficient number of stored muons in parasitic mode is incompatible with the present setup of the running AD experiments.

8 Conclusions

In the next years, CERN will focus on building and operating LHC. However, a large community is eager to maintain an active neutrino physics program. The CNGS long-baseline beam will start operation in spring 2005; the OPERA detector is already fully approved and under construction; a first 600 ton ICARUS module has already bee built and tested, and a proposal for a factor 5 mass increase is under approval. For the future, HARP is studying hadron production in the region of interest of present and future neutrino beams, neutrino factories and atmospheric neutrinos; there is an active group studying the possibility of a second-generation super-beam (possibly in conjunction with a beta-beam), and trying to make the first step towards a European neutrino factory for the post-LHC period.

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